Fermilab

http://www.fnal.gov

Studies for a Muon Collider Optics

Contents:

presented by Eliana GIANFELICE

eliana@fnal.gov

The situation so far

Basic Requirements:

- low β^* (<1 cm)
- small momentum compaction factor ($< 1\times10^{-4}$)
- large momentum acceptance
- sufficient Dynamic Aperture

Issues:

- large sensitivity to alignment and field errors
- large chromatic effects limit the momentum acceptance and require strong correction sextupoles
- large non-linearities limit the Dynamic Aperture

- Dipole First Optics (β^*=10 mm): local IR chromaticity correction *(à la Montague)* and 2 interleaved sextupole families in the FODO based arcs. Good energy acceptance, but small DA.

- Oide design (β^*=3 mm): non-interleaved chromaticity correction scheme. Good DA, large energy acceptance by playing with sextupoles (22 families), octupoles and decapoles. Strong sextupoles, very sensitive to misalignment errors (MCD Workshop, Dec 2007).

The "in loco" IR chromaticity correction has in general the advantage of a large energy acceptance range. This may be obtained in the non-local correction by optimising a *large number* of sextupole families, necessarily strong.

Local chromatic correction

Montague *chromatic functions* describing the change of the twiss parameters with momentum $\delta \equiv \Delta p/p$

$$B \equiv \frac{\Delta\beta}{\beta} \qquad \text{and} \qquad A \equiv \beta\Delta\left(\frac{\alpha}{\beta}\right)$$

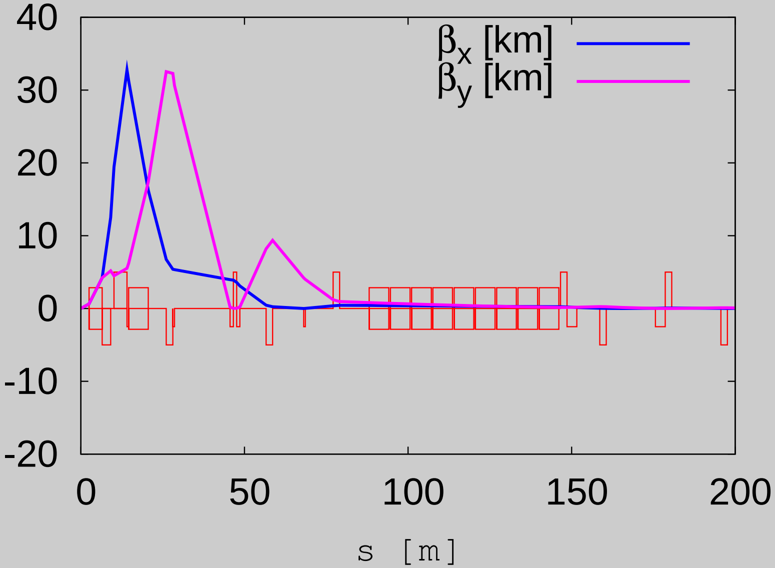
$$\frac{dB}{ds} = -2A\frac{d\mu}{ds} \quad \text{and} \quad \frac{dA}{ds} = 2B\frac{d\mu}{ds} + \sqrt{\beta(0)\beta(\delta)}\Delta K$$

As long as $d\mu/ds = 0$ it is $B=0$ (β and phase are momentum independent).

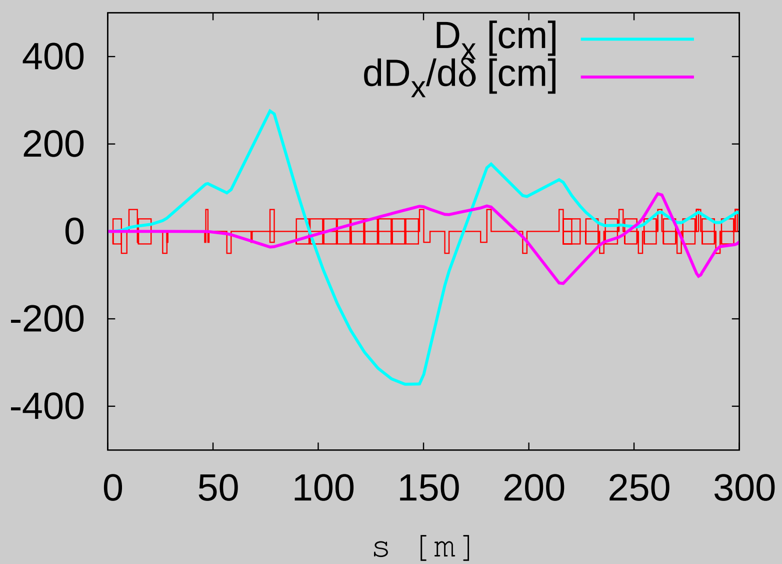
Idea: compensate the large chromatic beta wave created by the IR quadrupoles *locally*, that is before the phase advance changes after the first quadrupole. For $D_x = D'_x = 0$ at the IP, this requires introducing bending magnet close to the IP.

Dipole First Optics

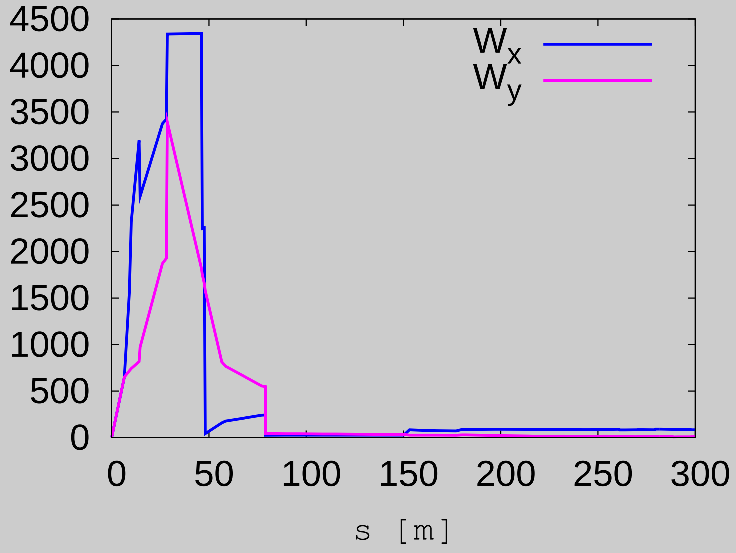
Introduce a dipole ($\boldsymbol{B}$=7.5 T, ℓ=4 m) before the first quadrupole to increase (wrt "Quad first") the dispersion at the IR sextupoles. Free space: $\pm$ 2.5 m



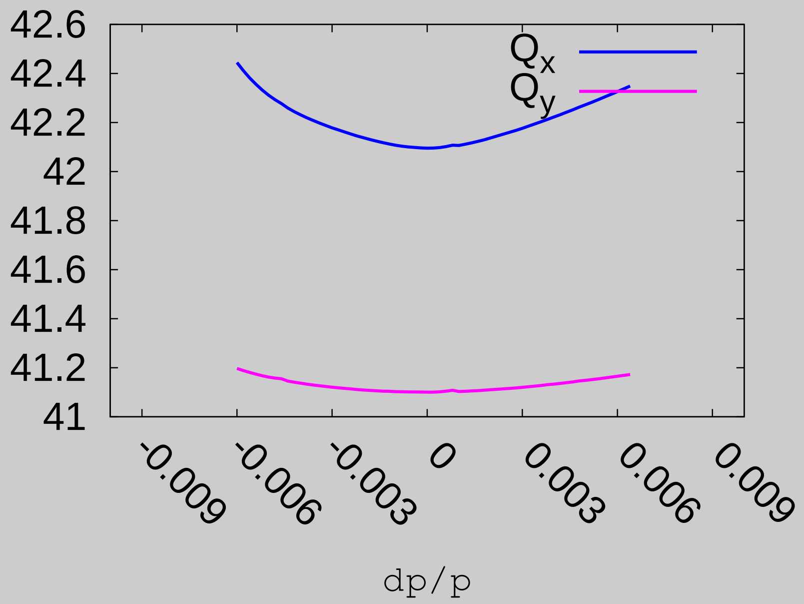
β



Dispersion

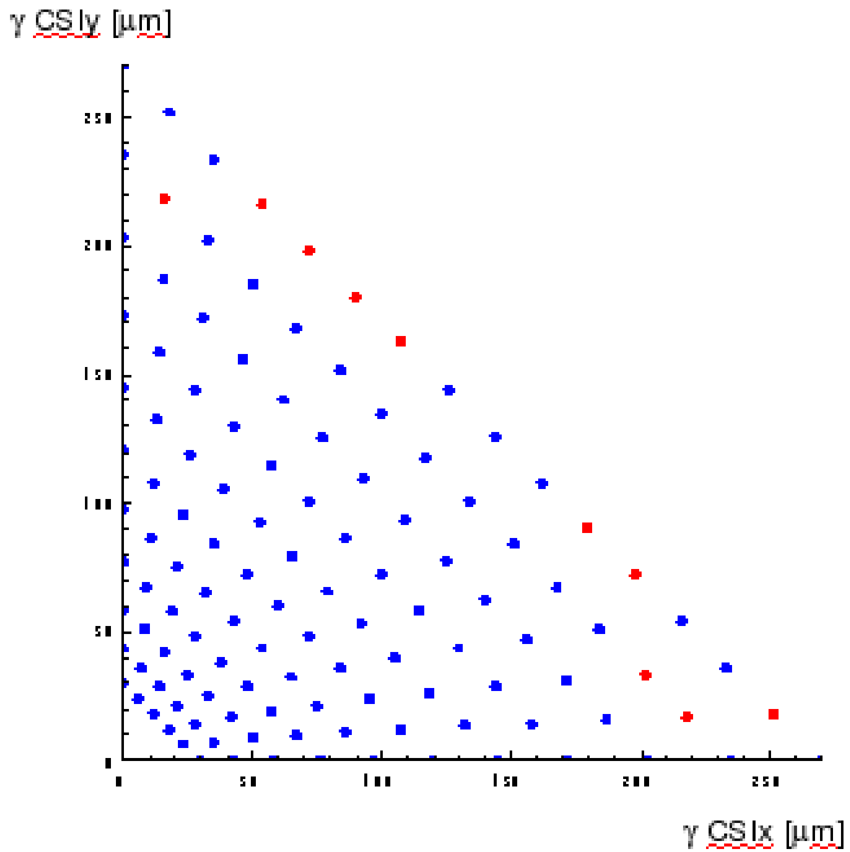


MAD chromatic functions



Tunes vs. dp

Yuri updated version (talk at Muon Collider Design Workshop, December 2008) shows large improvement of DA wrt NFMCC07 version.



One would expect

$$\gamma\, CSI_{\max} = \gamma\, \Delta Q / (dQ / dE) \approx$$
$$\approx 7 \cdot 10^{3} \times 0.4 / 2.4 \cdot 10^{8} \approx 120 \cdot 10^{-6}$$

```
Second order chromaticity:
Q1''      =   24074.96031867
Q2''      =    4020.58313978
Normalized anharmonicities:
dQ1/dE1 =  0.25242152E+08
dQ1/dE2 =  0.19616977E+08
dQ2/dE2 =  0.18515914E+08
```

The 1024 turns DA is now marginally sufficient for the high-emittance option: ~3σ for $\varepsilon_{\perp N}$=25 µm and is O.K. for low- and medium-emittance option.

It can be increased by compensating detuning with stronger octupoles

However:

- fringe fields not included yet
- optics errors will reduce DA
- we need good LONG-TERM DA to work with protons

Non-interleaved Sextupoles Optics

Oide original optics showed large sensitivity to misalignment errors (Yuri talk at MCD Workshop, Dec 2007), but a larger β^*, and thus more reasonable $\hat{\beta}$, should help.

The non-interleaved scheme requires an optics "ad hoc": the transfer matrix between couple of sextupoles must be a pseudo[a] $-I$ in *both* planes so that the kicks on a particle going through the two sextupoles cancel each other.

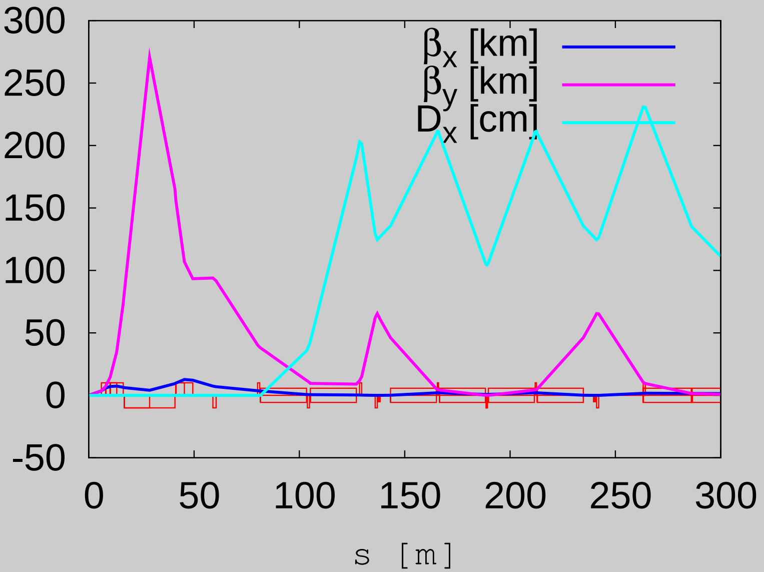
An attempt of introducing a non-interleaved sextupole correction *only* in the arcs by using 90 degrees FODO cells gave only a marginal improvement of the DA (NFMCC, March 08)

Playing with the dipole *bending radius* of 90 degrees FODO cells to get large dispersion and small α_p, as alternative to the "2.5 π" Oide cells, did not lead to shorter arcs (LEMC 2008).

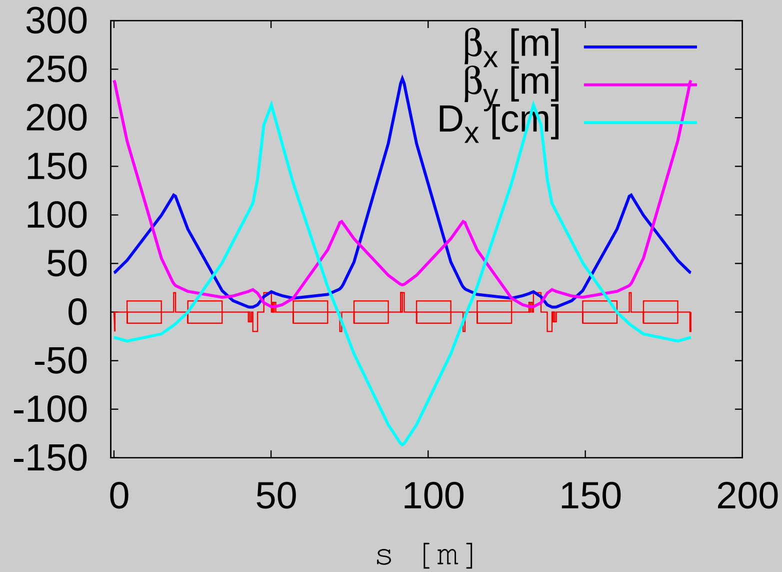
[a] $\alpha_1 \neq \alpha_0$

- IR magnets *unchanged* wrt Oide design, but β^* increased to 10 mm
- use 2.5π cells, but reduce magnet length (Oide bends: L=22 m long, B=3.7 T @ 750 GeV)
- use 2 different bending angles to get an handle on dispersion
- add a dispersion free section for RF cavities and tuning quadrupoles

IR



2.5π Cell

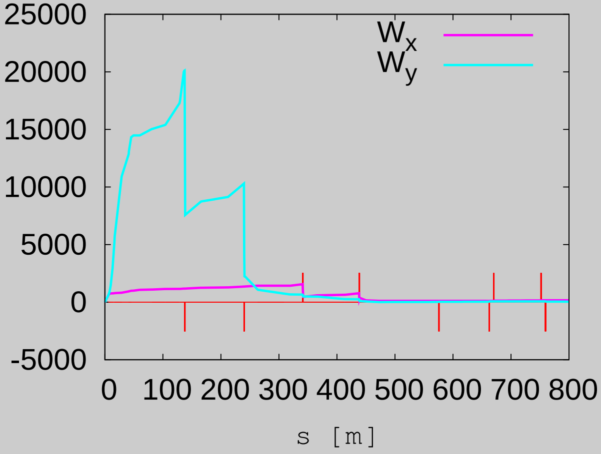


- $\boldsymbol{L}$=4855 m, one $\boldsymbol{IP}$, $\hat{\boldsymbol{\beta}}_{\boldsymbol{y}}$=275 Km (it was 900 Km)
- $\boldsymbol{Q_x}$=30.55, $\boldsymbol{Q_y}$=30.45
- $\boldsymbol{\alpha_p}$=1.8e-4

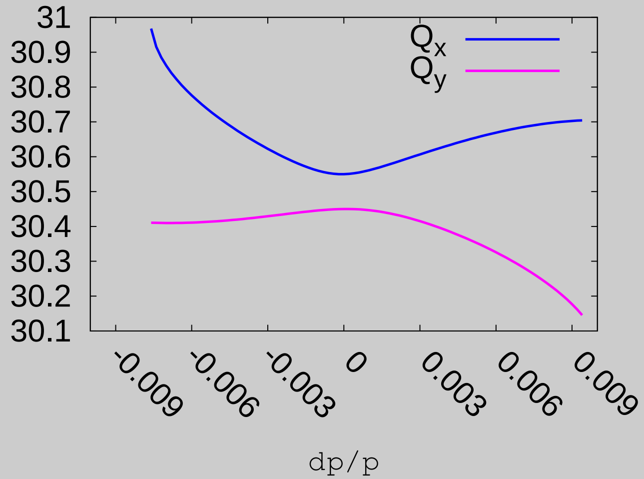
The tunes have been chosen to get maximum stability range under the assumption that the machine is stable near the half integer (KEKB does it!).

- IR chromaticity corrected with *one couple* of sextupoles per plane
- ring chromaticity corrected with *one family* per plane

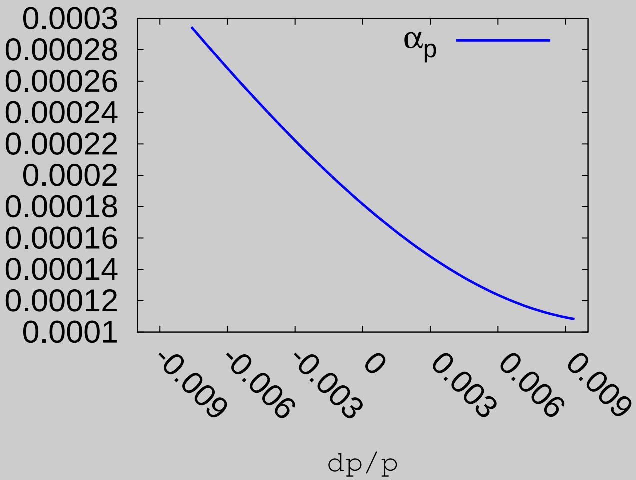
MAD chromatic functions



Tunes vs. dp/p



α_p vs. dp/p



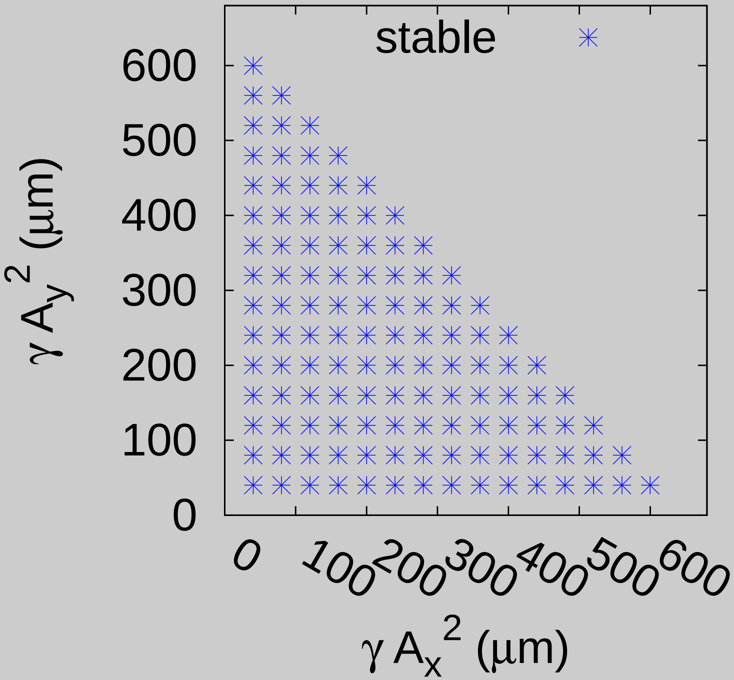
nb: the momentum compaction is too large for a 1 cm long bunch

Dynamic Aperture

Tune Dependence on Amplitude (no octupoles) *(MAD8 STATIC)*	
dQ_1/dE_1	0.50×10^3
dQ_1/dE_2	0.30×10^4
dQ_2/dE_2	-0.16×10^7

Dynamic Aperture (on energy)

(MAD-X PTC)

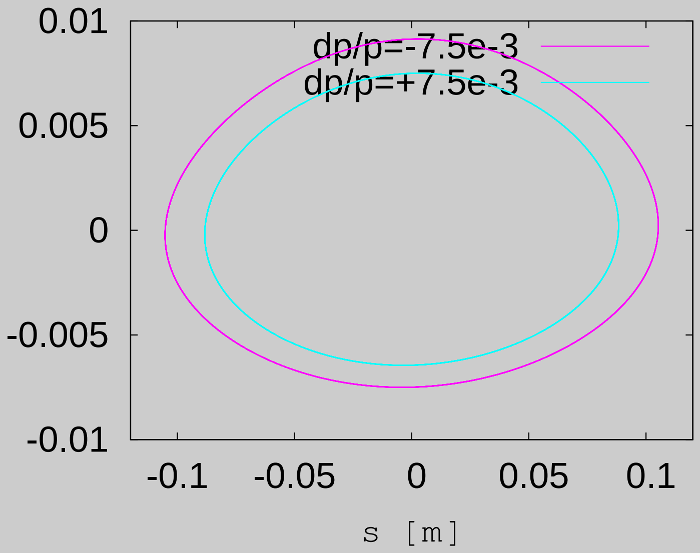


7 sigma's at least (ϵ_N=12.3 μm) !

The longitudinal phase space

The fact that $\boldsymbol{\alpha_p^0}$ is small makes higher order terms important:
trajectories in longitudinal phase space are *deformed* and the stable region is *asymmetric*!

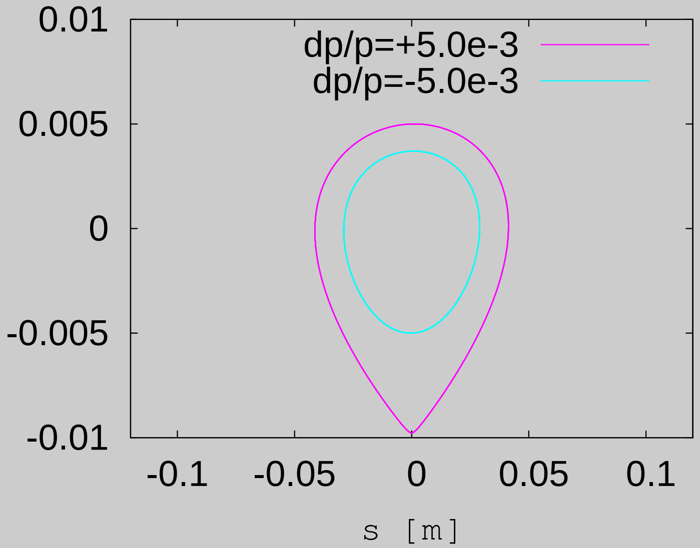
360 MV @ 600 MHz



a particle starting with (0,-7.5e-3) reaches $\boldsymbol{\Delta p/p}$=+9e-3 after half synchrotron period and is lost if the ring is not stable!

This effect *may reduce* further the energy range of the machine!

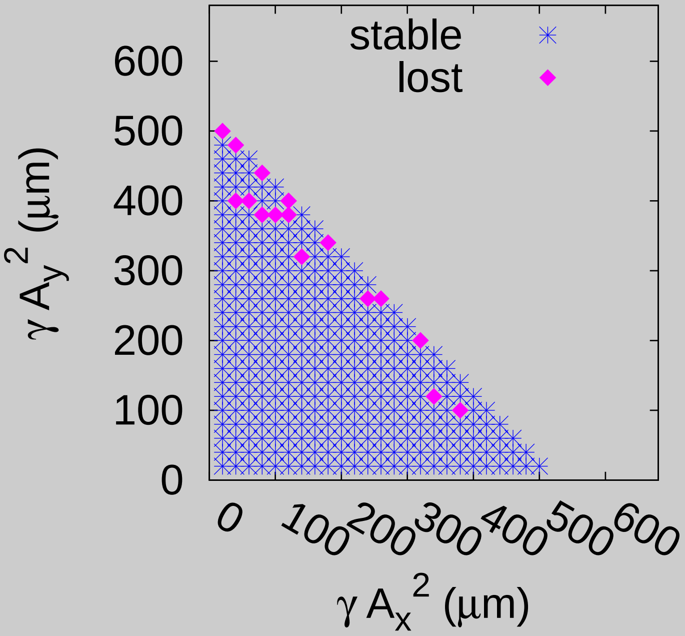
360 MV @ 600 MHz



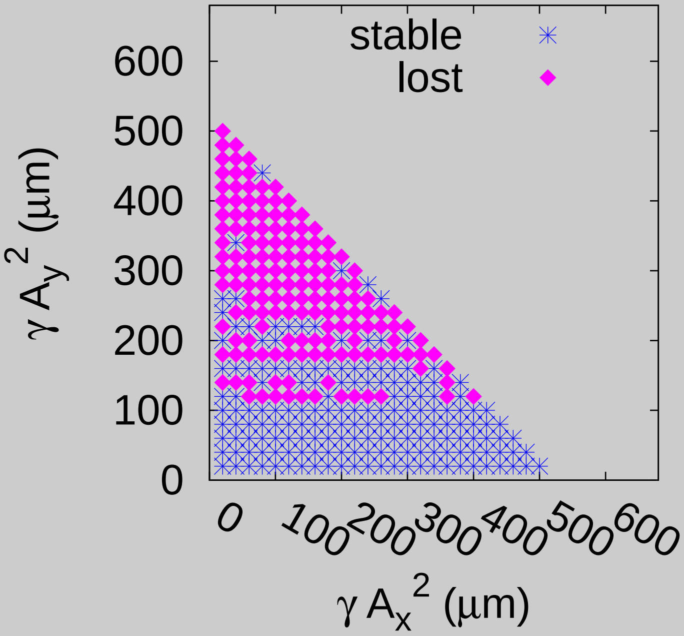
The effect is more evident for the “dipole first” optics, version with α_p= 9.7e-5. The $(dp/p)_{t=0}$=+5e-3 trajectory is obtained in 2th order approximation.

Off energy DA with Synchrotron Motion (MAD8)

$\Delta p/p$=5e-3



$\Delta p/p$=7e-3



Summary and Outlook

Idea: combine the best of the two chromaticity correction approaches!

Modifications to the "Oide-like" optics:

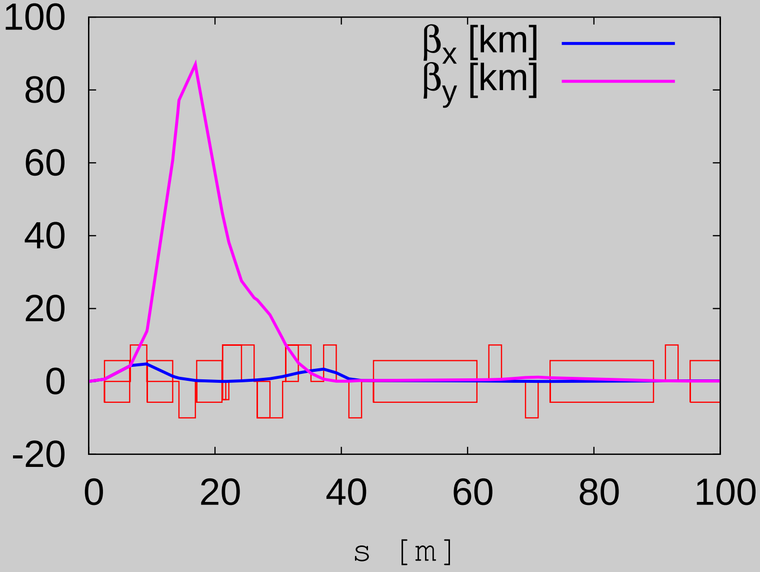
- re-design the IR, keeping the "asymmetry", allowing the β in the plane which chromaticity is *first* corrected to grow larger than the other one;
- use non-interleaved scheme for correcting chromaticity, but place first sextupole at $\Delta\mu$=0 from IR quads (the "dipole first" concept - it requires the insertion of dipoles in the IR); the fact that the phase advance across the IP is π allow to spare the twin sextupole.

If more convenient, the 2.5 π cells may be replaced by 90 degree FODO (NFMCC, March 08). In general: do we need the non-interleaved scheme also for the arcs?

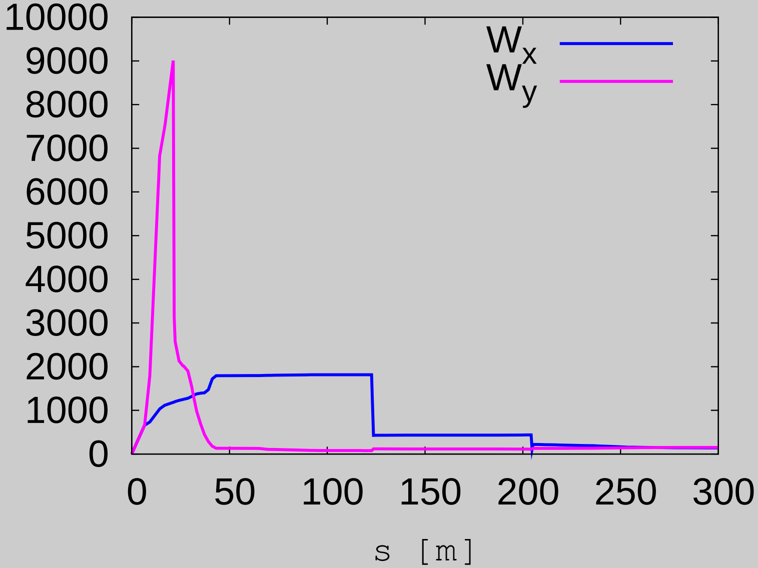
Modification to dipole first optics for improving the DA: keep IR sextupole correction concept for one plane , add a $-I$ section for the other plane. This could allow to drop the first dipole.

Attempts are underway of a non-interleaved sextupoles optics with re-designed IR and a dipole at 2.5 m from IP.

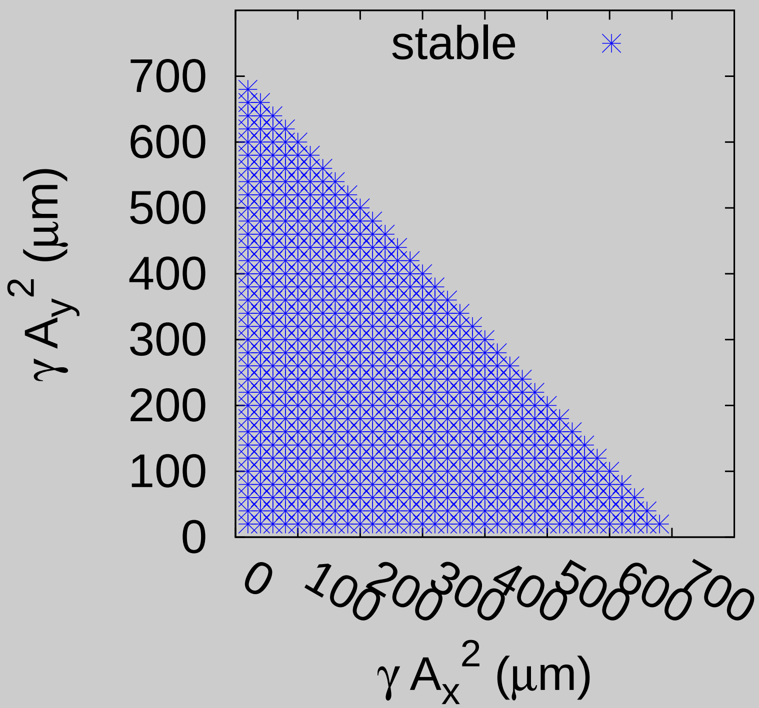
IR twiss functions



MAD chromatic functions



On energy DA



Having dropped the twin of the first pair of sextupoles did not affect the DA.

Linear optics not yet satisfying: too large dispersion, too large horizontal chromaticity, too strong magnets.

Acknowledgments

The expertise and guidance of Yuri are warmly acknowledged!